



Original communication

Forensic age estimation in living subjects based on ultrasound examination of the ossification of the olecranon



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ARTICLE INFO

Article history:

Received 9 February 2013

Received in revised form

11 October 2013

Accepted 7 December 2013

Available online 18 December 2013

Keywords:

Forensic anthropology

Age estimation

Ossification

Olecranon

Ultrasound

ABSTRACT

Radiation-free imaging procedures for the purposes of forensic age diagnosis are highly desirable, especially for children. With this in mind, the stage of ossification of the olecranon was prospectively determined in 309 male and 307 female healthy volunteers aged between 10 and 25 years, based on ultrasound. A four-stage classification system was used for this purpose. This stage classification system takes into account whether an isolated secondary ossification centre, an epiphyseal cartilage or an epiphysis which is completely fused with the diaphysis can be detected. The earliest observation of stage 2 was at 10.0 years in males and 10.1 years in females. Both findings are determined by the lower age limit of the sample and are thus not representative of the minimum age for ossification stage 2. Stage 3 was first noticed at age 13.5 years in males and 10.6 years in females. Stage 4 was first reached at age 13.7 years in males and 12.3 years in females. Hence, in our sample, ossification stage 3 can be seen as evidence that females have reached the age of 10 years and males the age of 13 years. In our sample, stage 4 provides evidence that a female individual has reached the age of 12 years. It was concluded that the results of our study should be validated using other samples.

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1. Introduction

Forensic age diagnostics in living juveniles and young adults have become increasingly important in recent years.^{20,2} Firstly, there have been reports from a number of West European countries relating to age estimation in adopted children originating in countries with no birth registries whose age was of interest, for example, in relation to the date of starting school. Forensic age estimations are also necessary to determine the asylum and/or minority status of juveniles and adolescents of dubious age arriving unaccompanied in West European countries. Furthermore, the necessity may arise to perform age estimations in accused persons without reliable birth dates to determine whether they have reached the age of criminal responsibility or the age at which adult criminal law is applicable. In the majority of countries the legal age limits are between the ages of 14 and 21.¹ Finally, it may be

necessary in the case of junior competitive sport to check dubious ages stated by sportspersons if there is ground for suspicion that athletes are trying to gain a competitive advantage by dishonest means.^{6,7}

The following range of methods for age estimation in living juveniles and young adults has been recommended by the Study Group on Forensic Age Diagnostics, provided that X-ray examinations are legally permitted²²:

- Physical examination with determination of anthropometric measurements (height and body weight, constitutional type), signs of sexual maturation and any developmental disorders that might affect age-appropriate development,
- X-ray examination of the left hand,
- Examination by a dentist with determination of the dental status and an orthopantomogram,
- Additional X-ray examination of the clavicles by means of computed tomography or projectional radiography for individuals in whom the hand skeleton is fully developed.

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The age of criminal responsibility is lower than 14 years in some countries, namely 10 years in England, Wales, Northern Ireland and Switzerland, 12 years in the Netherlands and Scotland and 13 years in France and Greece.⁵ It is therefore considered desirable to explore further skeletal regions in order to prove that the age limits in late childhood have been exceeded.

X-ray examinations for the sole purpose of forensic age diagnostics are not medically indicated. In some countries, this gives rise to the legally relevant question of whether exposure to radiation during these examinations is hazardous to health. A comparison between the effective doses of radiation of the X-ray examinations recommended by the Study Group on Forensic Age Diagnostics and exposure to natural and man-made radiation reveals that a relevant health risk need not be feared.¹⁹ The risks of mortality arising from the respective X-ray examinations, which have been calculated on the basis of the controversial assumption that random effects of radiation may also occur at low-dose levels of exposure, are comparable with the risks of mortality from other everyday activities such as road traffic participation.^{12,14,23} Until a conclusion has been reached concerning the biological effects of low-dose levels of radiation, it is imperative to keep radiation exposure to a minimum in all essential examinations and to avoid any exposure that is not absolutely necessary.

Children are more radiosensitive than adults,¹⁵ hence the establishment of radiation-free imaging procedures as a means of forensic age diagnostics is particularly relevant in this age group. Moreover, in areas of the law in which the person concerned must consent to the examinations required for age estimation, it may be assumed that those affected would be more inclined to agree to a radiation-free imaging procedure than to an X-ray examination. In light of this, the current study examined whether ultrasound examination of the ossification of the olecranon could be used for the purposes of age estimation.

2. Materials and methods

The proximal end of the right ulna was prospectively examined in 309 male and 307 female healthy volunteers who were fairly evenly spread across the age range from 10 to 25 years, with each year of age allocated to a separate cohort (Table 1). The study participants were recruited by means of advertisements in regional newspapers in the Münster area. The research was carried out with the consent of the volunteers and/or their parents in the case of minors. The study was approved by the ethics committee responsible. All volunteers were German citizens. No information on the socioeconomic status of the subjects was available, but it may be

assumed that the sample does not differ substantially from the average composition of the German population.

The examinations were performed using the DP-6600 (Mindray, Shenzhen, China) digital ultrasound scanner and a 7.5 MHz linear transducer. The necessary contact between transducer and skin was achieved by a stand-off pad (Fig. 1). All examinations were performed by a physician qualified and certified in the area of arthrosonography.

Based on the classification devised by Schulz et al.,²⁵ the degree of ossification was divided into 4 stages:

Stage 1: (No epiphysis.) Acute-angled end to the proximal extension of the diaphysis, absence of a secondary ossification centre.

Stage 2: (Epiphysis separate.) In the entire area examined, the proximal extension of the diaphysis is separated from the secondary ossification centre by the epiphyseal cartilage which presents an ultrasonic gap.

Stage 3: (Partial fusion of epiphysis and diaphysis.) Sectional planes with epiphyseal cartilage (ultrasonic gap) between the proximal extension of the diaphysis and the secondary ossification centre as well as sectional planes with a convexly curved end of the proximal ulna and without epiphyseal cartilage (ultrasonic gap) can be detected. Thus, within the examination area, some sectional planes display the findings of a stage 2, other sectional planes the findings of a stage 4.

Stage 4: (Complete fusion of epiphysis and diaphysis.) In the entire area examined, the end of the proximal ulna is curved with no epiphyseal cartilage (ultrasonic gap).

In Fig. 2 stages 2–4 are represented by schematic drawings and pictures. Figs. 3–5 show sonographical findings of an ossified epiphyseal center with a non-ossified epiphyseal plate, an ultrasonic gap and an ossification centre, as well as a curved end to the proximal ulna without an ultrasonic gap and finally a fully ossified epiphyseal plate.

The IBM SPSS software programme (Release 20.0.0) was used for statistical analysis. For each stage the following statistical values were calculated separately for each sex: minimum age, maximum age, mean with standard deviation, as well as median with upper and lower quartile. To cope with outliers and/or skew distributions, differences between the sexes were analysed using the Mann–Whitney *U* test for two independent groups. Significance was assessed at $p < 0.05$, exact, two-sided.



Fig. 1. Ultrasound examination of the ossification of the olecranon by means of a stand-off pad.

Table 1
Number of cases by age and sex ($n = 616$).

Age (years)	Male	Female
10	16	15
11	22	16
12	20	18
13	20	20
14	21	21
15	21	21
16	16	17
17	21	22
18	17	20
19	20	21
20	20	20
21	20	19
22	23	20
23	20	21
24	13	22
25	19	14
Total	309	307

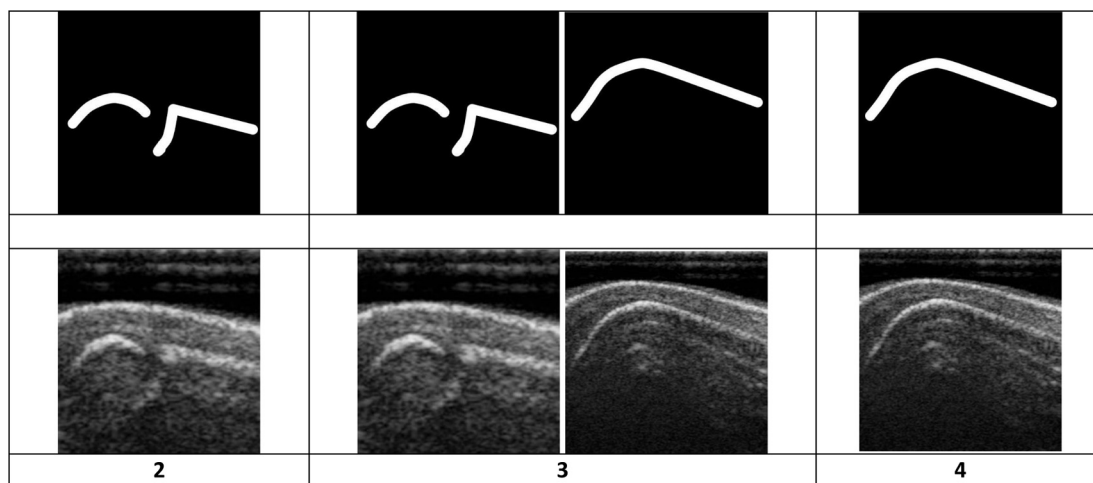


Fig. 2. Schematic drawings and pictures of ossification stages 2–4 (stage 2: epiphysis separate, stage 3: partial fusion of epiphysis and diaphysis, stage 4: complete fusion of epiphysis and diaphysis).

3. Results

The stage of ossification could be determined in 615 cases. In one case it could not be judged due to a history of fracture. Table 2 presents the minimum, maximum, mean \pm standard deviation and median with lower and upper quartiles for stages 2–4 separately for each sex. Stage 1 was not found in any of the cases examined.

The data obtained from both sexes reveal that over the entire age range studied, the minima and mean values of the chronological age increased with each stage.

The earliest observation of stage 2 was at 10.0 years in males and 10.1 years in females. Both findings are determined by the lower age limit of the sample and are thus not representative of the minimum age for ossification stage 2. Stage 3 was first noticed at age 13.5 years in males and 10.6 years in females. Stage 4 was first reached at age 13.7 years in males and 12.3 years in females. The mean values for stage 2 were 12.4 years in males and 11.6 years in females. The mean values for stage 3 were 15.0 years in males and 13.9 years in females. The mean values for stage 4 were 20.5 years in males and 20.0 years in females.

Statistically significant differences between the sexes were identified in stages 2 ($p = 0.004$) and 3 ($p = 0.001$), with female participants on average reaching these stages approximately one year before the male participants.



Fig. 3. Female, 11 years old, ossified epiphysis with a non-ossified epiphyseal plate, stage 2.

4. Discussion

In recent years the research interest in the field of forensic age diagnostics in living subjects has focussed on establishing radiation-free imaging procedures, resulting in the publication of results from MRI examinations of the distal radius, knee and clavicle.^{6,24,11,9,10,3} In addition, pilot studies have used ultrasound

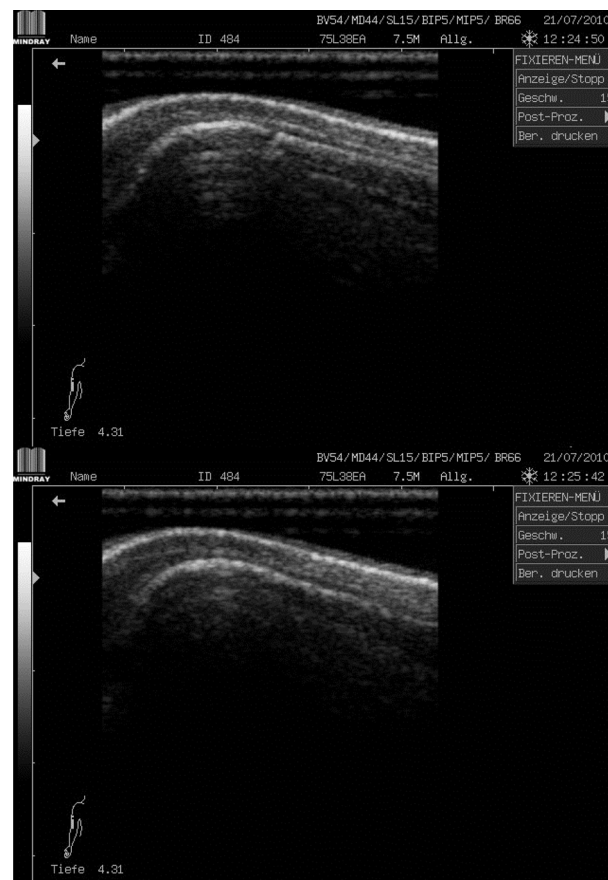


Fig. 4. Male, 15 years old, epiphyseal cartilage (ultrasonic gap) and an ossified epiphysis, as well as a curved end to the proximal ulna without the epiphyseal cartilage (ultrasonic gap), stage 3.

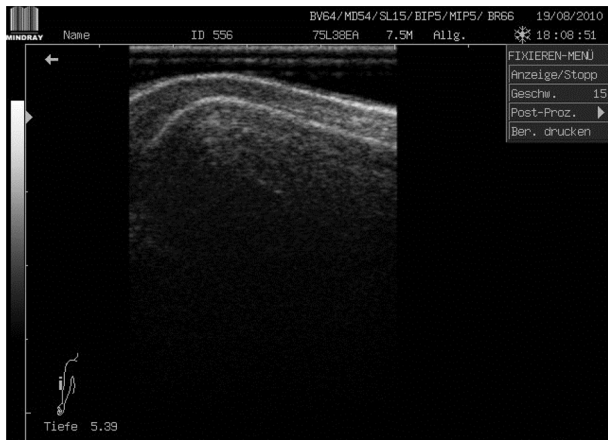


Fig. 5. Male, 25 years old, fully ossified epiphyseal plate, stage 4.

Table 2

Statistical parameters, in years and by sex, for ossification stages 2–4 ($n = 615$).

Stage	Sex	N	Mean \pm SD	LQ median UQ	Min–Max
2	Male	88	12.4 \pm 1.5	11.2 12.2 13.7	10.0–16.3
	Female	46	11.6 \pm 1.0	10.9 11.5 12.2	10.1–14.3
3	Male	19	15.0 \pm 1.0	14.0 15.0 15.8	13.5–17.7
	Female	32	13.9 \pm 1.1	13.2 13.9 14.6	10.6–16.8
4	Male	201	20.5 \pm 3.1	18.0 20.8 23.2	13.7–25.9
	Female	229	20.0 \pm 3.4	17.3 20.1 22.9	12.3–25.9

SD = standard deviation, LQ = lower quartiles and UQ = upper quartiles, Min = minimum, Max = maximum.

methods to examine the ossification of the radius, pelvis and clavicle.^{24,25,13}

Ossification of the elbow was also examined in order to assess clinical skeletal age in the age range of 10–15 years. Thus, Sauvegrain et al.¹⁶ developed a skeletal age assessment method based on anteroposterior and lateral X-rays of the elbow which takes into account the morphological stages of maturation of four epiphyses: the lateral condyle, humeral trochlea, olecranon and the head of the radius. A simplified version of the Sauvegrain method exclusively examines the epiphysis of the olecranon.⁴ It was noted that the epiphysis and metaphysis began to fuse at 12.5 years in female and 14.5 years in male subjects. Complete fusion of the epiphysis and metaphysis was observed in females at 13 years and in males at 15 years.

In osteological studies, open epiphyseal plates were observed in the proximal ulna until the age of 16 in males and 12 in females. Completely closed epiphyseal plates occurred in males at the age of 15 years at the earliest and in females at the age of 14 years at the earliest.¹⁷

The present study examined whether ultrasound examination of the ossification of the olecranon is possible and whether it could be applied for the purposes of forensic age estimation. Unlike X-rays, ultrasound can only access part of the bone surface when assessing the stage of ossification. Our study therefore adopted a classification system developed by Schulz et al.²⁵ for ultrasound assessment of clavicular ossification.

The individuals studied were aged between 10 and 25 years, thus accounting for the age bracket subject to forensic age estimation. Since an uneven age distribution within the sample can lead to systematic over- or underestimation of age,⁸ this study – with a few exceptions – included 20 male and 20 female individuals in each of the one-year cohorts.

The minimum ages of the stages of ossification are of particular significance to age estimation, since they can confirm that an

individual's age is above the relevant limits. The minimum ages for stage 2 in our study were defined by the lower age limit of the study participants. Since the cut-off age of our sample is 10 years, it cannot be said with any degree of certainty that stage 2 might occur in an individual younger than 10 years. The minimum age for stage 3 was 10.6 years for females and 13.5 years for males. Thus, the presence of stage 3 can be seen as evidence that female individuals have reached 10 years and male individuals 13 years. Stage 4 was first found in the female study participants at the age of 12.3 years, while in the male participants it was seen at 13.7 years at the earliest. In our sample, this stage provides evidence that a female individual has reached the age of 12 years. The results of our study should be validated using other samples.

One important question of practical relevance is whether the results of our study can be applied to subjects of different ethnic origin. In an extensive survey of the literature on the time frame for ossification of the hand, which is regarded as representative of the overall skeletal system, Schmeling et al.¹⁸ concluded that ethnic origin does not apparently exert any notable influence on the rate of ossification within a particular age group. By contrast, the socioeconomic status of the sample does have a decisive impact on the pace of ossification. It may be assumed that there is a genetically determined potential for skeletal maturation available for exploitation under optimum environmental conditions (i.e. high socioeconomic status), whereas a less favourable environment may lead to retardation of skeletal maturation.²¹

In principle, ultrasound imaging is a fast, cost-effective and widely available, radiation-free alternative to X-ray assessment of olecranon ossification. The use of ultrasound imaging can thus considerably improve the accuracy of age estimations in areas of the law which provide no legitimation for X-ray examinations. However, one of the limitations of ultrasound is the difficulty to objectively document the findings of the examination. This significantly limits the degree of reliability of potential reassessments. For the purposes of forensic age estimation, therefore, it is recommended that the findings to be established and subsequently agreed upon by at least two independent examiners.

5. Conclusions

- The stage of ossification of the olecranon can be determined by means of ultrasound.
- In our sample, ossification stage 3 can be seen as evidence that females have reached the age of 10 years and males the age of 13 years.
- In our sample, stage 4 provides evidence that a female individual has reached the age of 12 years.
- The results of our study should be validated using other samples.

Ethical approval

The study was approved by the ethics committee responsible.

Funding

This work was supported by the fund “Innovative Medical Research” of the University of Münster Medical School (SC 1 2 07 18).

Conflict of interest

The authors declare that there are no conflicts of interest.

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